Terahertz Imaging and Backscatter Radiography Probability of Detection Study for Space Shuttle Foam Inspections

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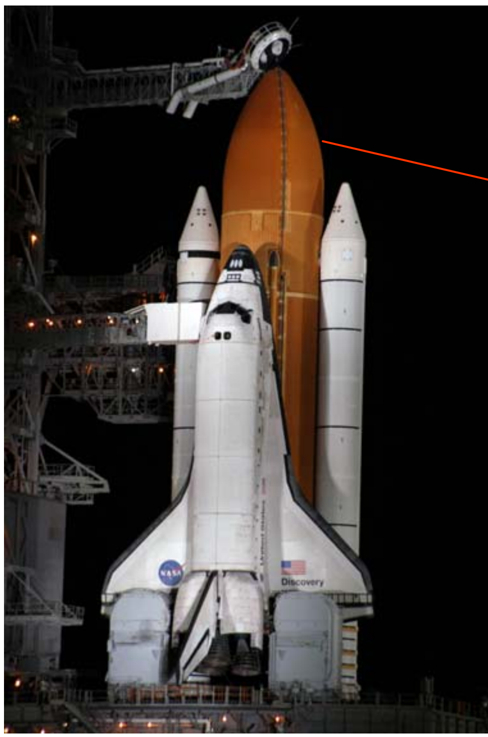
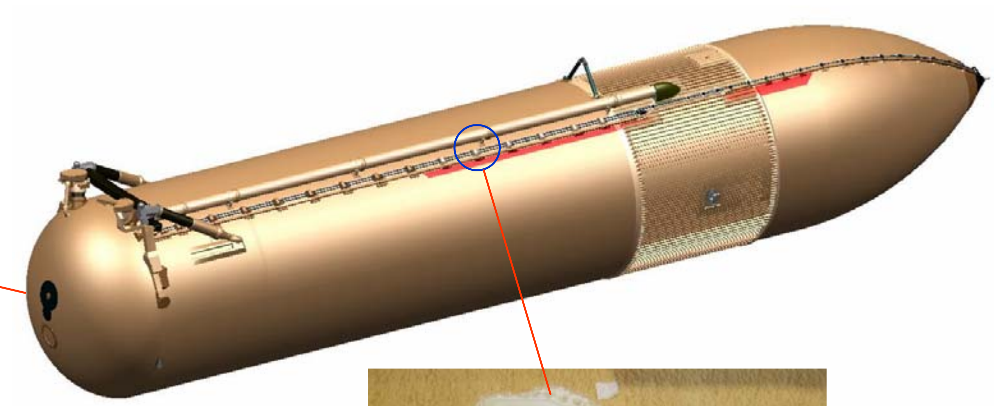
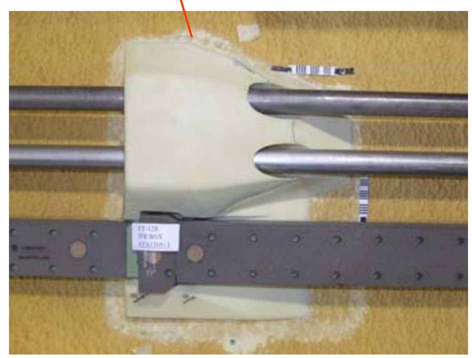
Background: External Propellant Tank

- **External Propellant Tank (ET) Background**
  - ET holds cryogenic liquid hydrogen and oxygen fuel for shuttle main engines
  - Polyurethane foam insulation prevents cryogenic fuel from boiling as well as ice formation
  - Aero loads during launch can produce foam debris potentially damaging the shuttle orbiter
  - After the Columbia accident, ET foam debris was identified as a likely cause of the orbiter wing damage
  - NDE is performed on ET foam as one method of preventing critical foam debris during launch





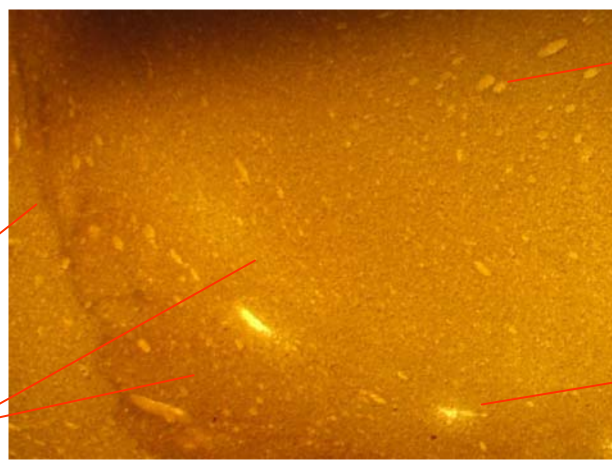


Ice frost ramps are one application that currently undergoes NDE on each External Tank.

Background: Foam Insulation

- **NDE Difficulties in Polyurethane Foam Inspection**
  - Does not lend itself to conventional NDE methods
  - Very low density (~2.5 lbs/cu ft) so air voids do not exhibit significant density change
  - Non homogeneous material with density variations
  - Inspection must be single sided due to access restrictions
  - No history of industrial inspection of foam

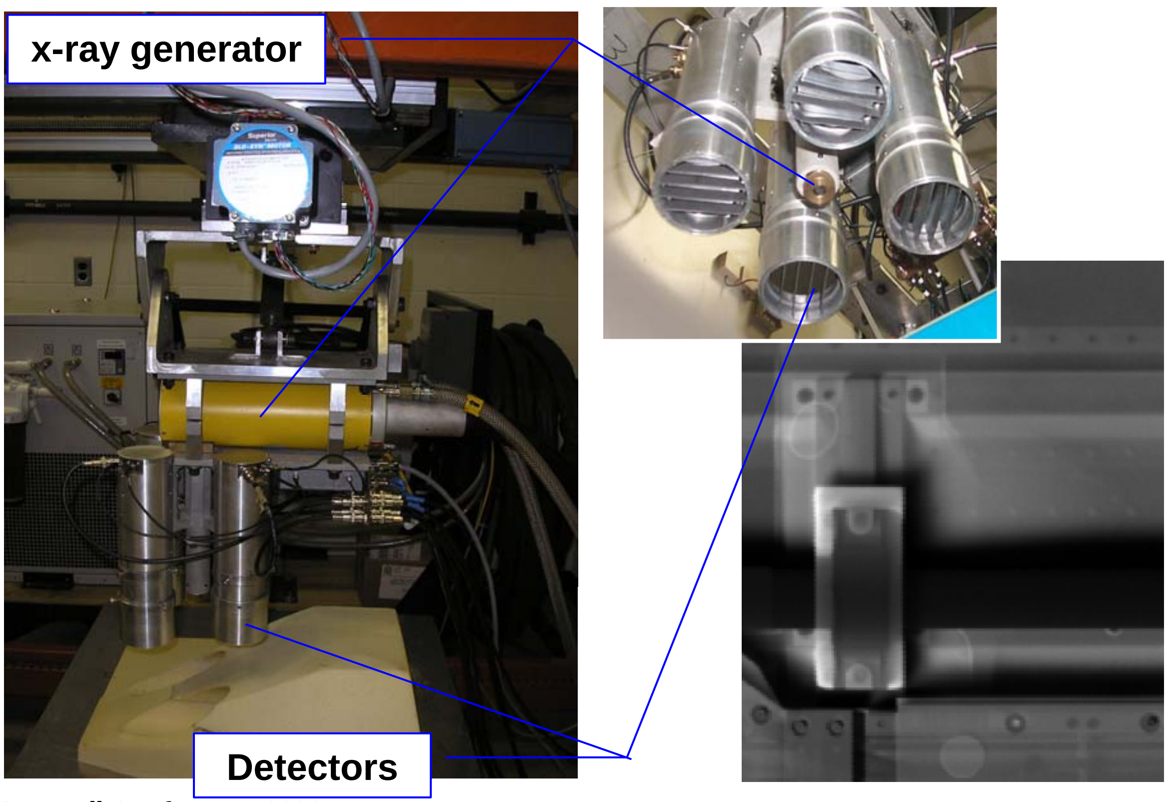
- **Conventional NDE Method Assessment**
  - UT: Foam attenuates UT
  - X-ray: Requires two sided access
  - Thermography: Foam is an insulator
  - Air-Coupled, Low Freq. UT: Non-homogeneous foam structure impairs technique

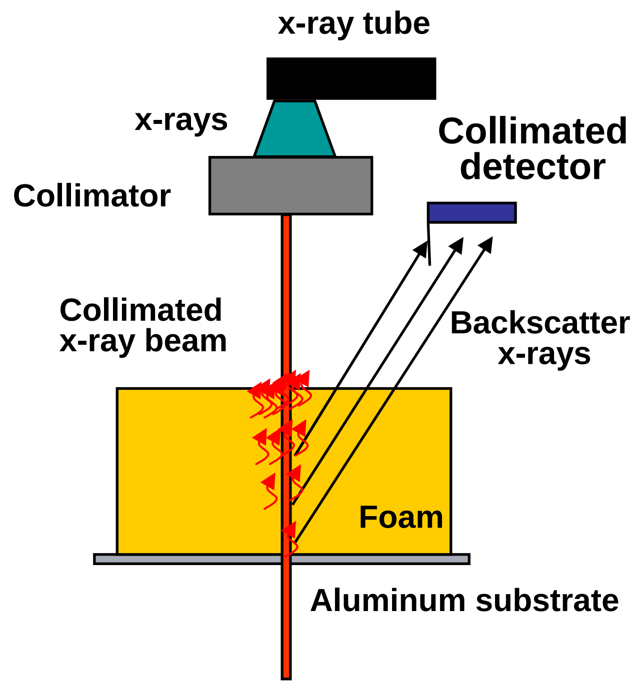


Typical Slice of ET Foam (Backlit to Emphasize Density Variations and Voids)

Background: Backscatter Radiography (BSX)

- Collimated beam of x-rays (55-70 kV) interact with sample molecules
- Backscatter x-rays are emitted (Compton Scattering), possibly after multiple subsequent scattering events, and detected by NaI or YSO detectors
- Collimation provides some preferential sensitivity to selected depth
- The x-ray beam and detectors are scanned across the part to generate a 2-D presentation of the internal make-up of the foam

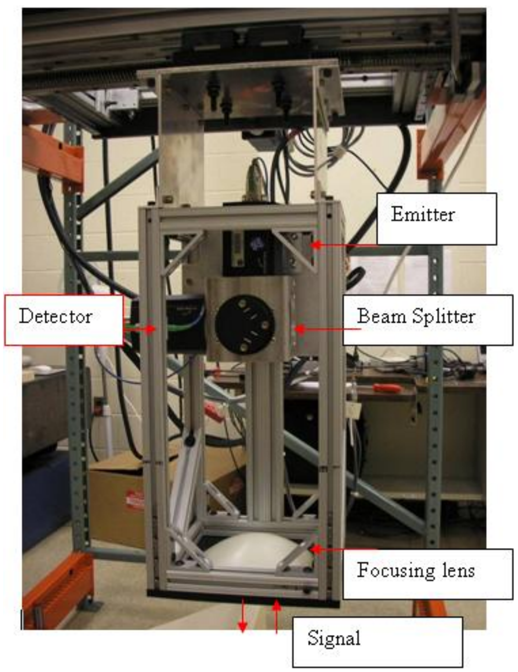




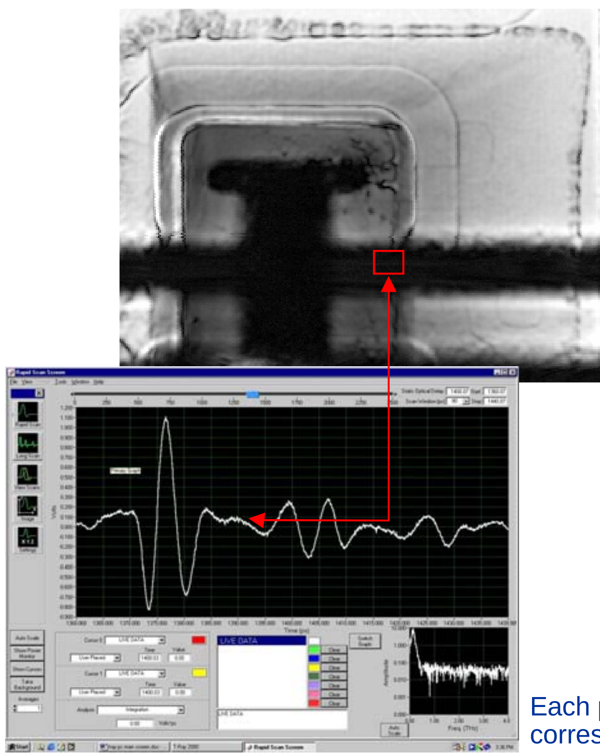
BSX Image

Background: Terahertz Imaging

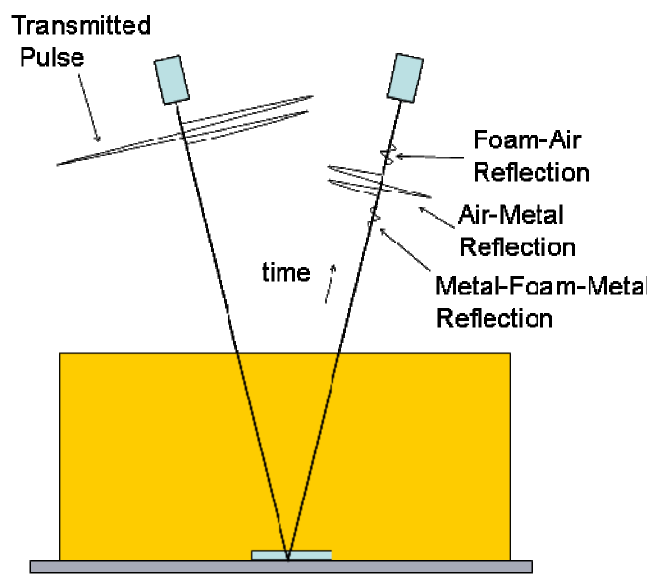
- Terahertz (THZ) inspection uses energy in the high frequency RF band between microwave and infrared
- THZ beam is transmitted through object and reflects off the aluminum substrate
- Due to foam attenuation, received pulse is approx. 0.1 to 0.3 THz (100 GHz to 300 GHz)
- Presence of defects produces changes in amplitude, phase and frequency of received beam
- Less attenuation can indicate less material such as the presence of a void
- THZ beam is scanned across the part to generate a 2-D presentation of the internal make-up of the foam



Terahertz Transceiver

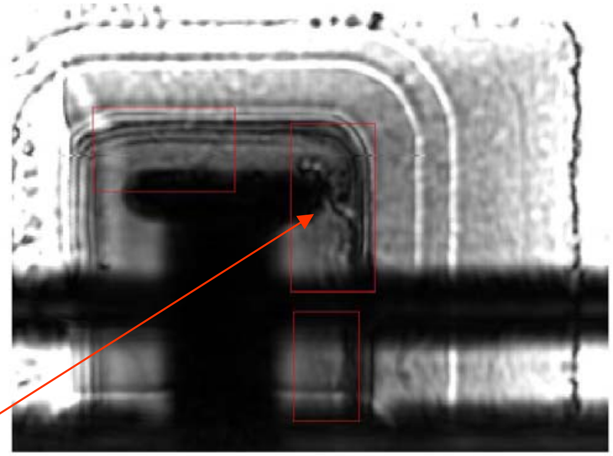


Each pixel in the Terahertz image corresponds to an individual waveform

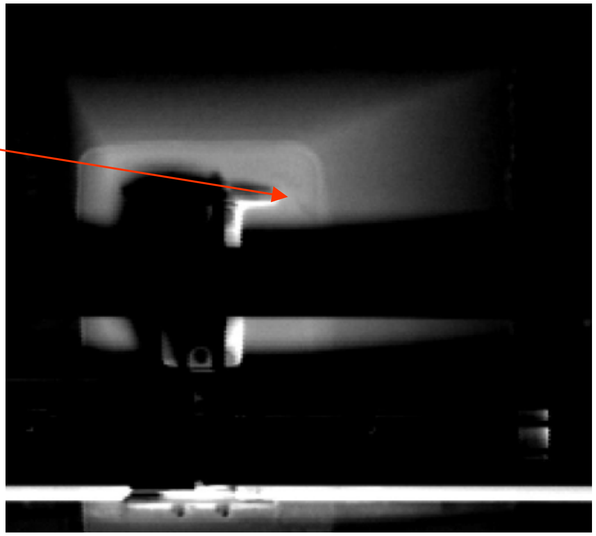


Background: BSX and THZ Examples

- **Example 1**
  - THZ image has distinct response from void
  - BSX image has marginal response from void



THZ image

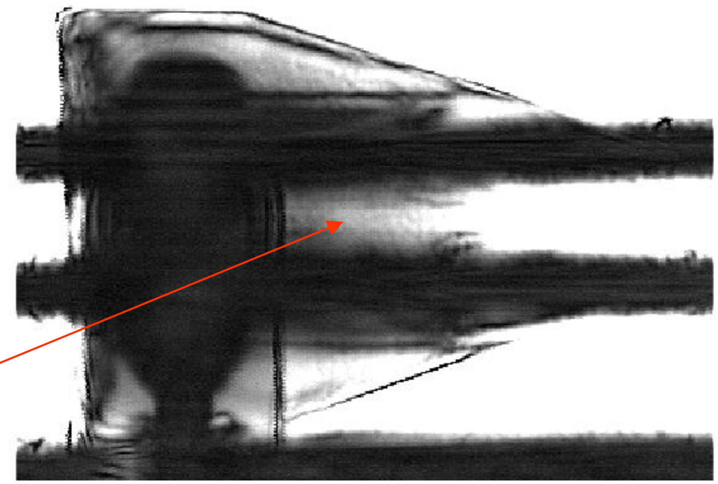


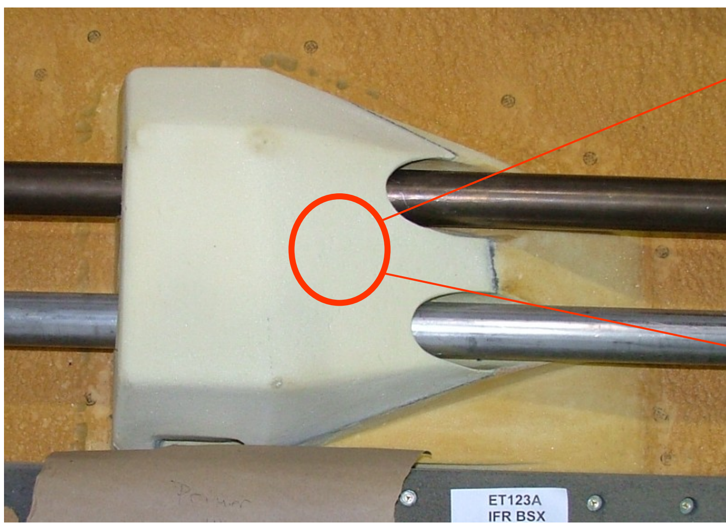
BSX image

Background: BSX and THZ Examples

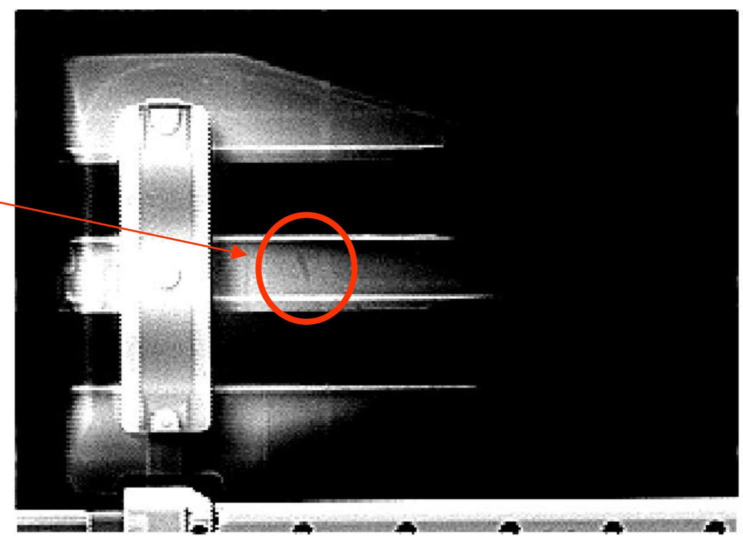
- **Example 2**
  - BSX image has distinct response from void
  - THZ image has marginal response from void

THZ image

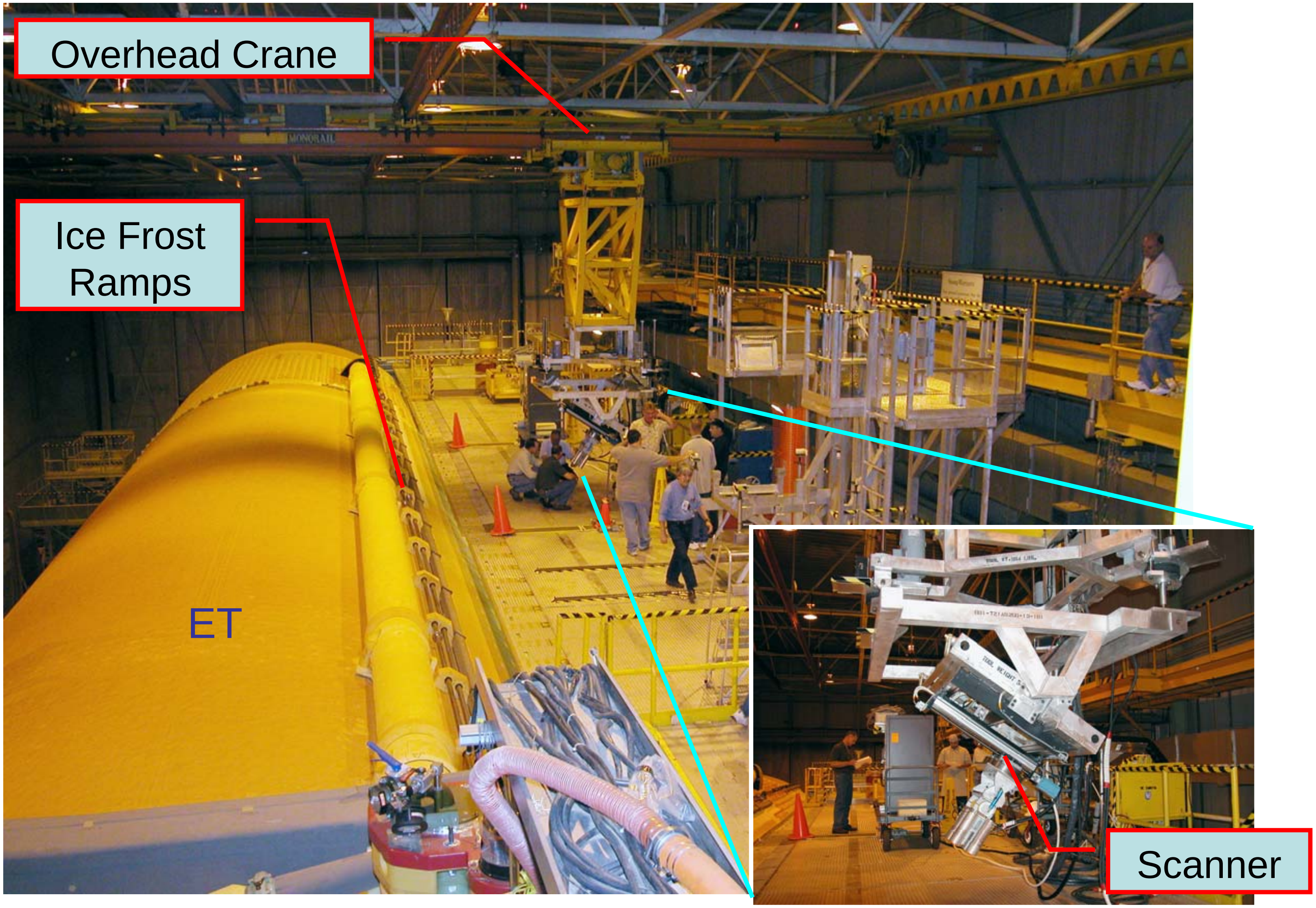




BSX image



EXTERNAL TANK FOAM INSPECTION SYSTEM



NDE Activity in Building 420 at the Michoud Assembly Facility

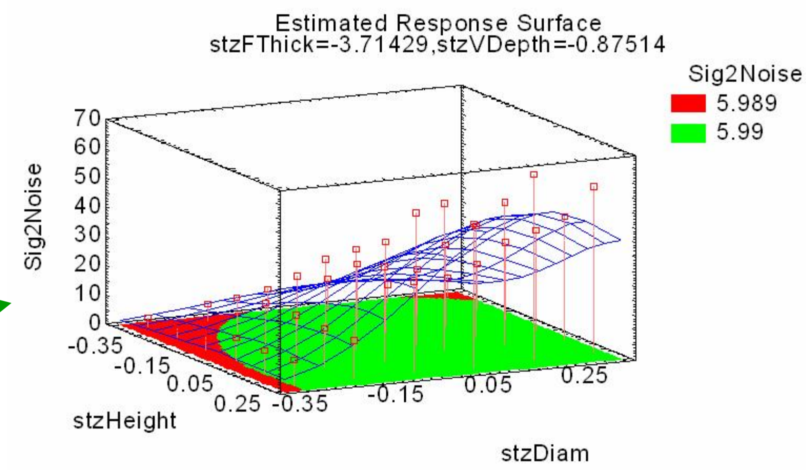
BSX/THZ POD Study

- **Purpose of Probability of Detection (POD) Study**
  - **Statistical study used to assess performance and reliability of an NDE method**
  - **90/95 detectability/confidence is common requirement in NASA, Air Force, etc.**
  - **BSX and THZ are used in a unique application with no existing POD history**
  - **POD result is necessary for future certification**

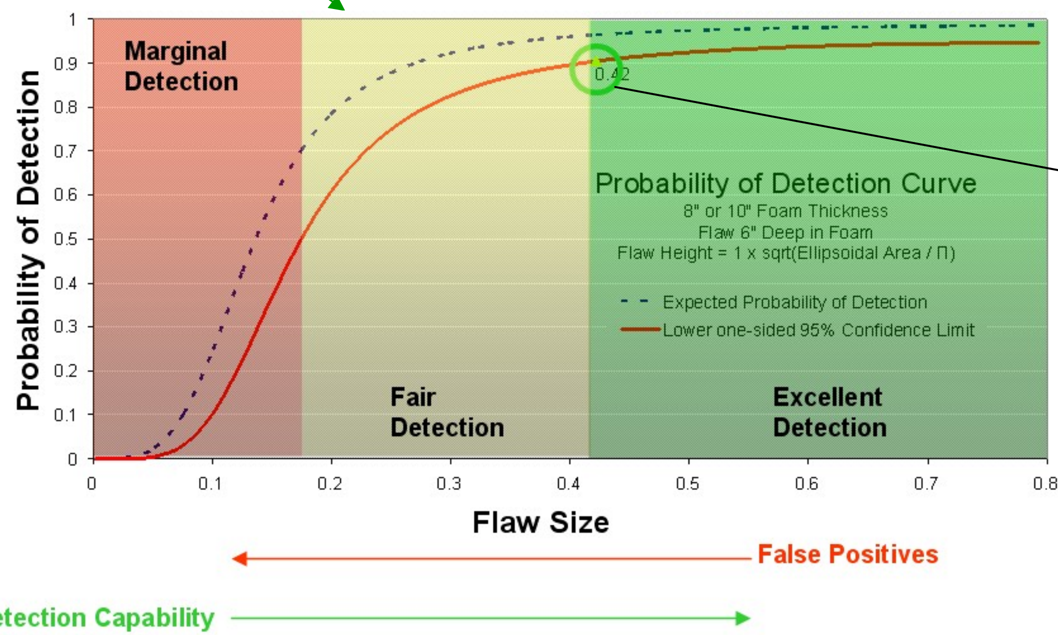
- **Goals for the BSX/THZ POD Study**
  - **Follow guidelines in MIL-HNBK-1823**
  - **Follow production requirements in inspection procedure**
    - **BSX and THZ methods are combined for a single result**
    - **Certified personnel**
    - **Material configuration**
    - **Production test procedures**
    - **Production equipment configuration**
  - **Establish 90/95 POD result**
    - **Multiple material thicknesses**
    - **Multiple defect depths**
    - **Exceed critical defect requirement of 0.9“ by 0.4” voids**
  - **Establish false positive rate**
  - **Provide pedigree to techniques and personnel**

BSX/THZ POD Study

- **POD Study Characteristics**
  - **Designed Experiment**
  - **Hit or Miss Data**
  - **Multi-Variable Logistic Regression**
  - **Cumulative Distribution Function**



Single variable versus multi-variable POD response



90/95 Value: Intersection of 95% confidence curve with 90% probability of detection

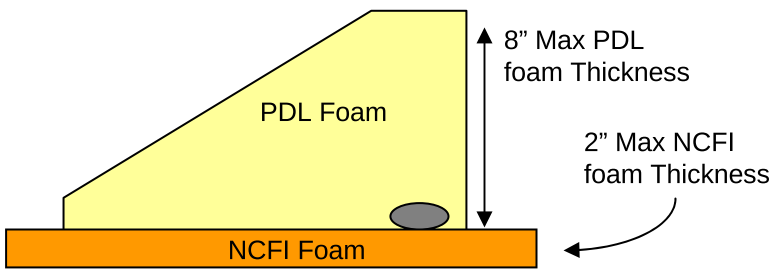
BSX/THZ POD Study

– POD Approach for BSX/THZ of Ice Frost Ramps (IFRs)

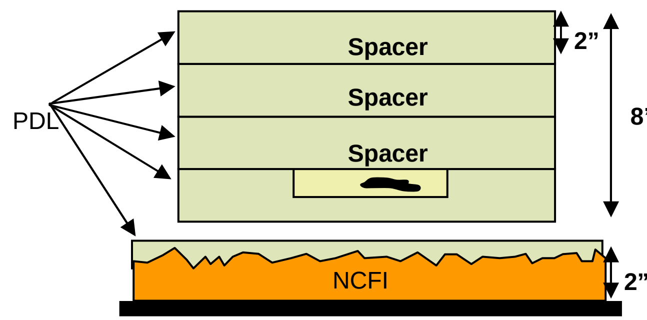
- Test article consisted of flat blocks with inserted semi-natural defects
- This design allowed POD calculation for different defect depths and foam thicknesses
- Sample population of 400 composed of 100 defects and 300 blanks
- A POD sample consisted of a BSX and THZ inspection of one coupon
- Three interpreters analyzed the 400 samples for a total of 1200 discrete results

POD test article

ET Ice Frost Ramp



Key materials and dimensions

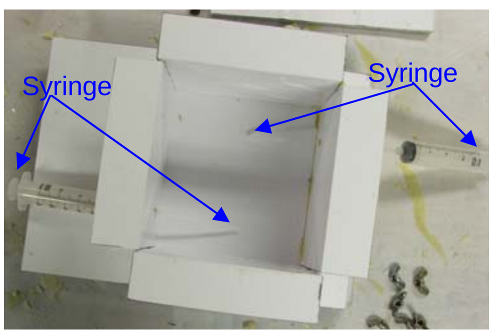


POD test article configuration

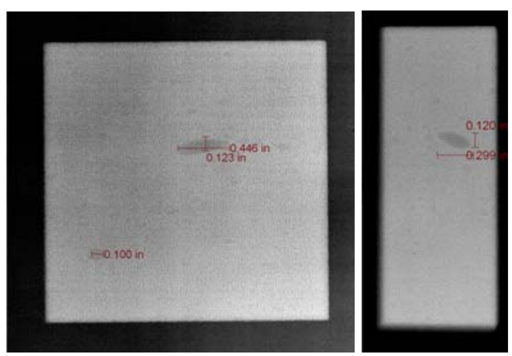
BSX/THZ POD Study

- **POD Approach for BSX/THZ of IFRs**
  - **Test matrix and experimental design:**
    - **Ken Johnson (MSFC Statistics and Trending group)**
    - **Ward Rummel (Independent Contractor)**
  - **Randomized inspection order**
  - **Interpreters were blind to sample contents**
  - **Three Level II certified radiographers evaluated data**
  - **All 400 samples were dissected to confirm defect sizes or false positives**

Coupon with defects after final dissection



Mold and syringes used to produce voids.

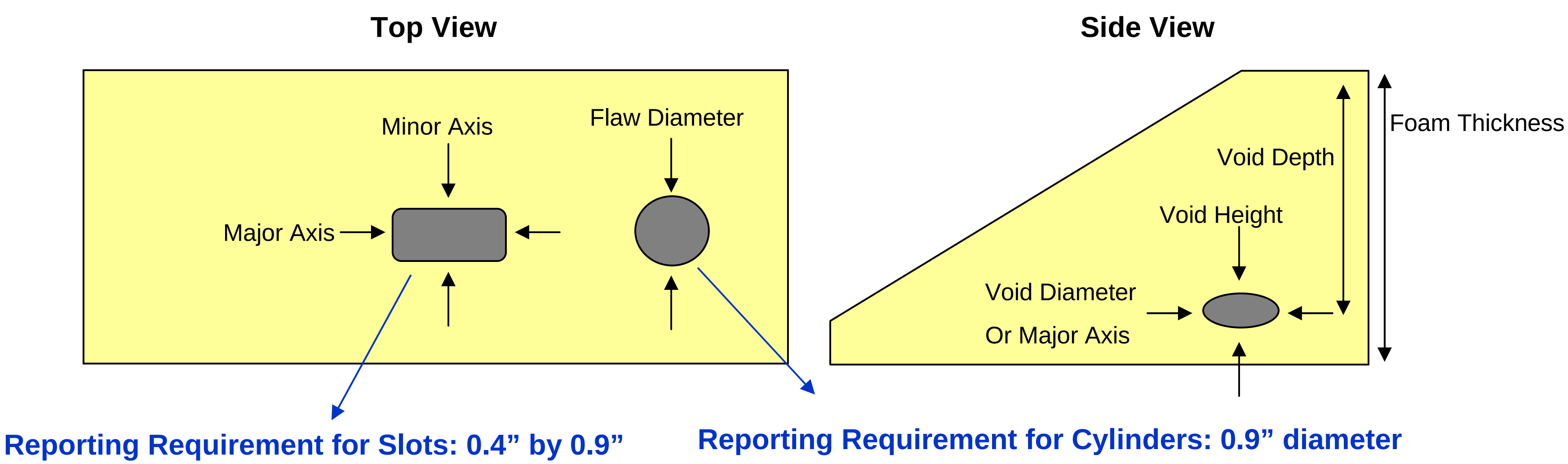


X-ray images of internal voids in coupon

Coupon with defects marked after x-ray inspection

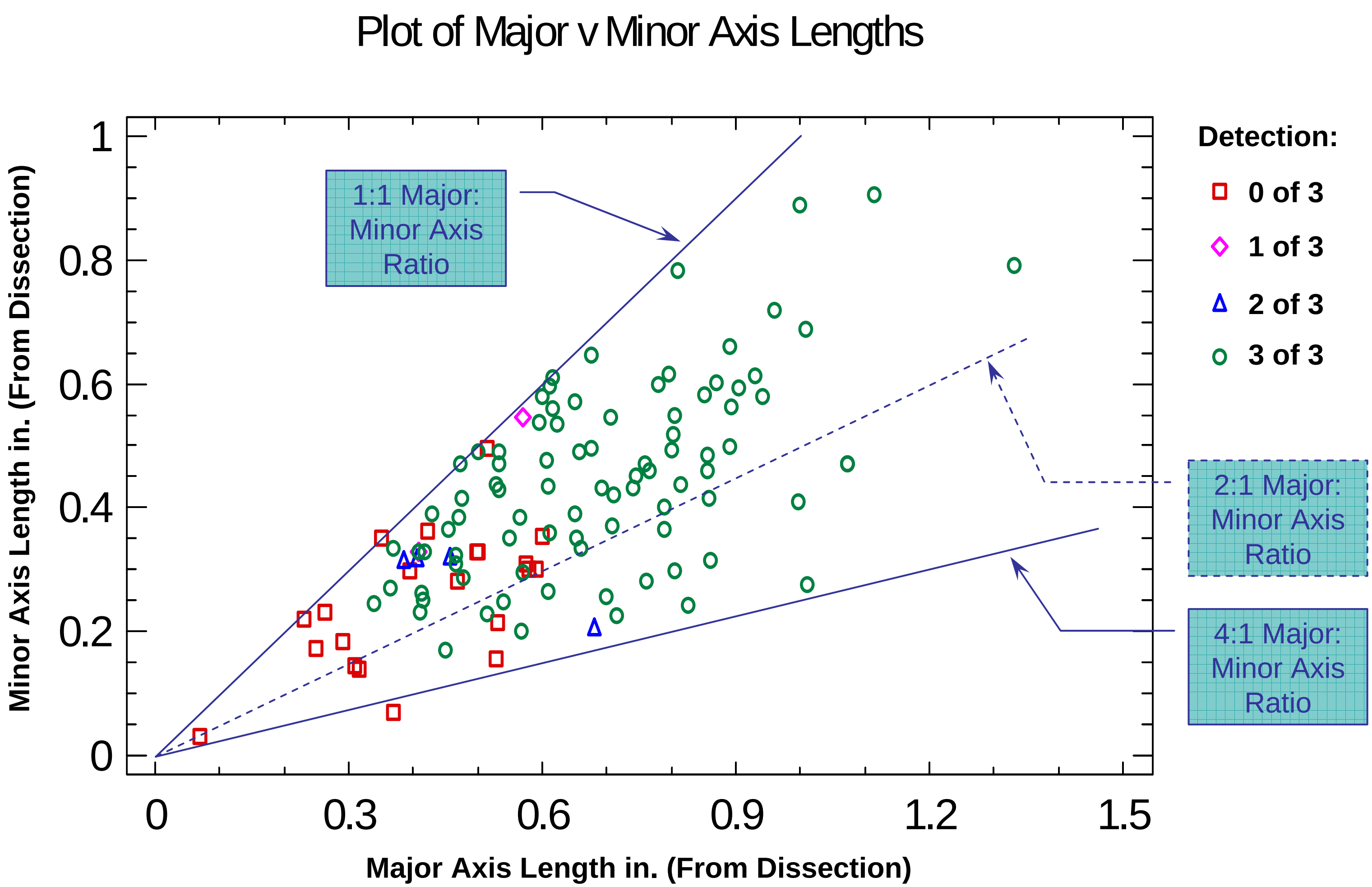
BSX/THZ POD Study

- **POD Variables**
  - **POD results are computed for multiple values of these variables**
    - **Interpreter: Three interpreters were used in the study**
    - **Foam thickness: Total foam thickness that contained the defect**
    - **Void depth: How far below the surface the void was located**
    - **Void height: Air gap or thru thickness of void**
    - **Void diameter: Diameter of cylinder void**
    - **Void major axis: Length of major axis of a slot void**



BSX/THZ POD Study

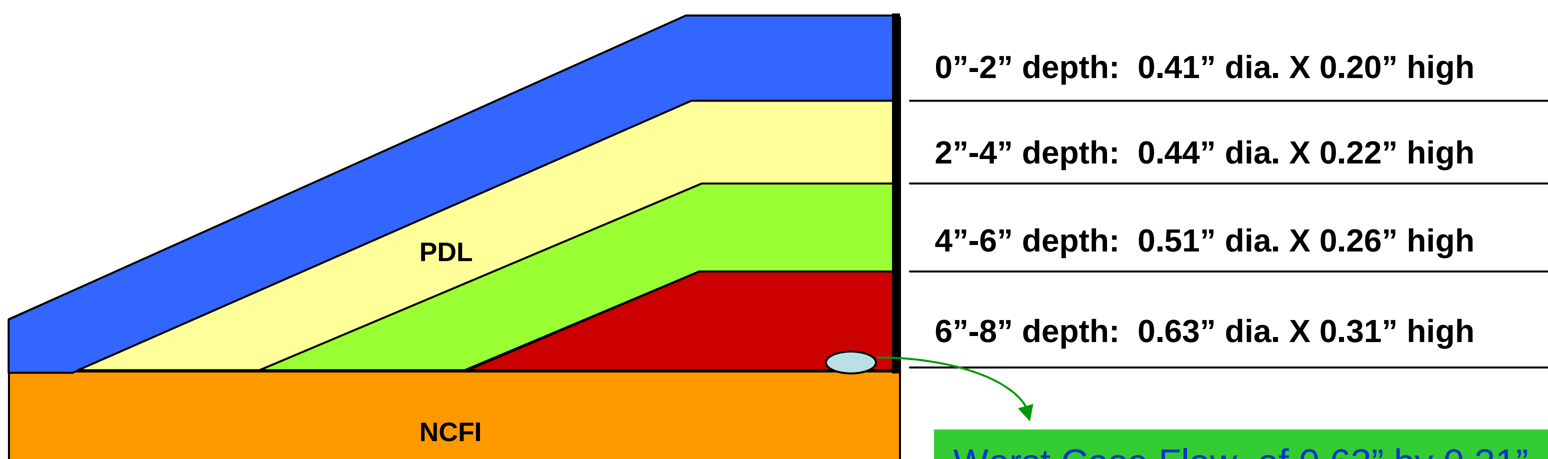
- **Observations**
  - **More elongated flaws require larger major axis dimension for detection**
  - **Thinner flaws (smaller height or thru-thickness) require larger major axis dimension for detection**
  - **Deeper flaws (under larger amounts of foam) require larger major axis dimension for detection**



BSX/THZ POD Study

- **POD Results for Combined BSX/THZ Inspection: Cylinders**

Inputs			90/95 POD Value
Foam Thickness (in)	Void Depth (in)	Flaw Height (in)	Flaw Diameter (in)
10	2	0.20	0.41
10	4	0.22	0.44
10	6	0.26	0.51
10	8	0.31	0.63

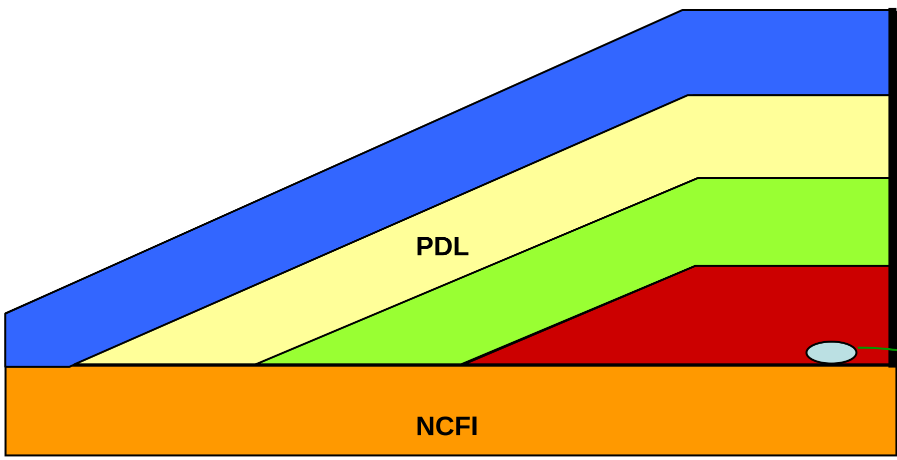


Worst Case Flaw of 0.63” by 0.31” Exceeds Critical Flaw Size Requirement of 0.9” dia.

BSX/THZ POD Study

- **POD Results for Combined BSX/THZ Inspection: Slots**

Inputs			90/95 POD Value
Foam Thickness (in)	Void Depth (in)	Flaw Height (in)	Flaw Maj. Axis (in)
10	2	0.29	0.58
10	4	0.31	0.62
10	6	0.36	0.72
10	8	0.44	0.89



0”-2” depth: 0.58” major axis X 0.20” high

2”-4” depth: 0.62” major axis X 0.22” high

4”-6” depth: 0.72” major axis X 0.26” high

6”-8” depth: 0.89” major axis X 0.31” high

Worst Case Flaw of 0.89” by 0.44” Meets Critical Flaw Size Requirement of 0.9” by 0.4”

BSX/THZ POD Study

- **BSX/THZ false positive results**
  - **False positive rate was approx. 0.24 per square foot or approx. one false positive per IFR**
  - **However, all false positives were below the reportable size of 0.4” x 0.9”**
  - **No false positive indications from this study would have been formally reported based on their small size**

All false positives were below reportable size of 0.4” x 0.9”

Inter-preter	Spl No.	ID	Lab Cpn. No.	Foam Thickness	BSX Hit/Miss	BSX Long Axis Dim.	BSX Short Axis Dim.	THz Hit/Miss
1	023a	Blank260	62B1X	4	1	0.580	0.220	0
1	023b	Blank260	62B1X	4	1	0.250	0.180	0
1	027	Blank046	76BX	4	1	0.930	0.250	0
3	082	Blank064	191X	4	1	0.235	0.235	0
2	181b	84.625	198BX	2	1	0.480	0.140	0
2	181c	84.625	198BX	2	1	0.550	0.210	0
1	295	Blank038	334X	4	1	0.250	0.120	0
3	362a	Blank175	384B1X	6	1	0.325	0.300	0
3	362b	Blank175	384B1X	6	1	0.300	0.300	0
1	400	Blank030	444X	2	1	0.160	0.160	0
2	382	Blank101	396B1X	8	1	0.360	0.260	0
2	400	Blank030	444X	2	1	0.170	0.150	0

- **POD Summary**
  - POD Test Plan was developed following the guidelines of MIL-HNBK-1823
  - ET production procedures were used in the POD study
  - POD studies completed for combined BSX and THZ detection of voids
  - Worst case 90/95 POD value for BSX/THZ:
    - Cylinders: 0.63” diameter by 0.31” thick void under 8” of foam
    - Slots: 0.89” x 0.45” slot by 0.31” thick void under 8” of foam
  - False positive rate established
    - No false positive results at or above critical flaw size